(12)

A RAND NOTE

AD A129077

ENHANCED RADIATION BELTS AND SYSTEMS IMPLICATIONS WORKSHOP

Cullen M. Crain

March 1983

N-1986-ARPA

Prepared for

The Defense Advanced Research Projects Agency

35th Year

Rand
SANTA MONICA, CA. 90406

The research described in this report was sponsored by the Defense Advanced Research Projects Agency under ARPA Order No. 3584-6, Contract No. MDA903-81-C-0471, Strategic Technology Office.

Published by The Rand Corporation

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER N-1986-ARPA	2. GOVT ACCESSION NO. AD-A129077	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Enhanced Radiation Belts and Systems Implications Workshop		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Cullen M. Crain		8. CONTRACT OR GRANT NUMBER(s) MDA903-81-C-0471
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Rand Corporation 1700 Main Street Santa Monica, CA. 90406		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Department of Defense Arlington, VA 22209		12. REPORT DATE March 1983
		13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

No Restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Radiation Belts	Spacecraft
Magnetosphere	Nuclear weapon debris
Radiation Hazards	Nuclear Explosions

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See reverse side

DD FORM 1 JAN 73 1473

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The Enhanced Radiation Belts and Systems Implications Workshop's objectives were (1) to determine the degree of understanding of the effects on space systems produced by enhancement of the natural radiation belts, (2) to identify the areas where additional understanding is needed, and (3) to provide suggestions for further research. The Workshop discussed many topics relevant to enhanced radiation belts and their potential effects on the architecture of enduring space systems. Topics included injection of trapped radiation from fission debris, loss mechanisms and lifetimes, SPECTER codes for predicting total radiation flux, mission considerations of trapped radiation, hardware vulnerability and hardening, single event phenomena, and planning for a chemical release satellite.

PREFACE

At the 1980 Workshop on Strategic Communications, sponsored by the Defense Advanced Research Projects Agency, nuclear effects and their influence on strategic system architecture received much attention. The possible effects of trapped radiation from very high altitude nuclear bursts and the degree to which the radiation may influence the architecture of future space systems, particularly those expected to endure in the event of nuclear hostilities, were considered to be important issues in need of better understanding. Subsequently, DARPA convened the Enhanced Radiation Belts and Systems Implications Workshop, held at The Rand Corporation, July 27-28, 1982. This Workshop had the objectives of (1) determining the degree of understanding and the importance of the effects on space systems which may be produced by enhancement of the natural belts, (2) illuminating the areas where additional understanding is needed, and (3) providing suggestions for needed further research by DARPA or others.

This Note provides documentation of the 1982 Workshop--including information on the participants, the agenda, the material presented, and a summary discussion of the more important topics considered.

CONTENTS

PREFACE iii

Section

I. INTRODUCTION 1

II. DISCUSSION OF SESSION ACTIVITIES 3

A. Review of Past and Current Programs 3
B. Review of Artificial Belts 4
C. Injection 5
D. Loss Mechanisms and Lifetimes 6
E. SPECTER Description and Assessment 6
F. Trapped Radiation--Mission Considerations 7
G. Aspects of Hardware Vulnerability 8
H. Single Event Phenomena 8
I. Other Contributions 9

III. SUMMARY COMMENTS 11

Appendix

I. Address List 13

II. Agenda 16

I. INTRODUCTION

A workshop sponsored by the Defense Advanced Research Projects Agency (DARPA) on Enhanced Radiation Belts and System Implications was held during July 27-28, 1982, at The Rand Corporation in Santa Monica, California. Recent studies on survivable and enduring capabilities for surveillance and communications using space assets have indicated that trapped radiation from high altitude nuclear bursts is an important influence in determining preferred system approaches. At the 1980 DARPA Workshop on Strategic Communications, nuclear effects and their role in influencing strategic system architecture received much attention. Trapped radiation has a particularly important role for enduring satellite systems operating from near earth orbits to somewhat beyond synchronous altitude.

Production and maintenance of artificial trapped radiation in the earth's magnetosphere involve many complex phenomena. The phenomena considered most important were examined in the Workshop and are discussed in this Note.

Limited understanding of some aspects of the enhanced radiation problem was gained from the U.S. high altitude tests in 1958 and 1962 and the USSR high altitude tests in 1962; however, most of our current understanding is dependent on theoretical analyses and study of the natural radiation belts. In 1958 the potential military implications of artificial trapped radiation received considerable national attention and resulted in Project ARGUS, sponsored by the Defense Advanced Research Projects Agency. Attention was directed to possible effects on warheads and decoys, space interdiction of both manned and unmanned systems, radar and communication noise generation, and local and conjugate point effects on radio systems with ionospheric transmission paths. Following the small yield (1 to 2 kT) bursts at a few hundred miles altitude over the South Atlantic in August and September of 1958 and a month-long review and assessment by national experts, the role of trapped radiation received less attention than other nuclear-related military effects. Probably the principal reason for less emphasis on

artificial trapped radiation derived from the popular belief that nuclear war would probably involve large-scale exchanges over a short period of time relative to the time required to inject belts with sufficient artificial radiation and the time required (days to months) for the integrated radiation doses to produce system degradation or demise.

In recent years policy and planning have been directed much more toward enduring capabilities of space and other systems. As a result, the potential role of trapped radiation effects has become much more important in determining preferred system architectures for best attaining enduring capabilities. This increased importance has naturally led to questions as to how well we understand the many phenomena involved--how good are the current prediction models with such injection factors as burst yield, altitude and latitude, loss mechanisms and lifetimes, maximum (or saturation) levels of trapped radiation attainable as a function of altitude and the earth's magnetic field parameters, multiple burst effects, and so forth. Quantitative accuracy is necessary to reasonably assess hardware vulnerability and system life expectancy.

DARPA invited 22 experts in the areas most relevant to the desired overall assessment to participate in the two-day Workshop. Sixteen of the 22 attendees (see Appendix I) presented prepared contributions to the agenda given in Appendix II. All the visual material presented has been reproduced and distributed to the attendees.

II. DISCUSSION OF SESSION ACTIVITIES

A. REVIEW OF PAST AND CURRENT PROGRAMS

Dr. Joseph Janni of the Air Force Weapons Laboratory was the chief discussant in this session. He described the research funded by the Defense Nuclear Agency (DNA) and the Air Force Weapons Laboratory (AFWL) which he had directed for many years. His presentation left several important impressions, including the following:

1. Research on enhanced radiation belts and their effects on space systems has not received high priority attention since the mid 1960s. As discussed in the introduction, enduring systems and long term survivabilities were not of major interest until recent DoD policy changes were indicated. Consideration of enduring system capabilities over weeks to months increases the need to better understand the factors determining system vulnerability to enhanced radiation belts.
2. Although computer codes have been developed to predict environments which may be produced by high altitude nuclear bursts, there are many valid questions about several of the ingredients in the codes and hence about their outputs. The current codes, despite known shortcomings, represent the best guidance now available. Their improvement will require both theoretical and experimental developments which are not currently supported. To adequately quantify system vulnerabilities we need improved understanding of injection of the trapped particles, loss mechanisms and lifetimes, and maximum levels of trapping throughout the magnetosphere--for both single and multiple burst environments.
3. The SPECTER Code is a valuable computational tool for estimating the trapped radiation environment produced by high altitude bursts. Improving confidence in its accuracy will require much more work on the code ingredients than is planned or possible with current funding.

4. Little effort has been expended on operational considerations such as how one would most efficiently inject debris to populate a given magnetic shell (e.g., size of burst, burst altitude, latitude, and spacing), how much fission yield is required to produce a given level of trapped radiation, and other questions.

B. REVIEW OF ARTIFICIAL BELTS

Dr. Martin Walt introduced this session with a comprehensive review of the artificial belts produced by high altitude nuclear explosions in 1958, 1961, and 1962. Although many data were obtained by instrumented satellites--primarily in 1962--major problems in assessing the characteristics of the belts produced by the nuclear explosions arose from uncertainties in the instrumentation then available, the limited spatial coverage of the satellites, and the general lack of agreement in the data obtained from different satellites. Major points clarified by the tests included (1) injection efficiencies of about 10 percent can be attained, (2) atmospheric collision effects are reasonably well understood, and (3) pitch-angle diffusion characteristics and L-shell diffusion behavior were determined empirically but are not completely understood. Remaining major uncertainties included the role of various injection mechanisms and saturation effects, including limiting fluxes and lifetimes on various L-shells for a range of electron energies and for various mechanisms of redistribution and loss.

Captain Bob Greaves gave a brief description of an AFWL-sponsored Trapped Radiation Data Base project at McDonnell-Douglas. The purposes of this project are to assemble all available data from satellite and rocket measurements of weapon-injected electron radiation belts to compare SPECTER and associated code calculations with the experimental data and to review and remodel codes to better reproduce the experimental data for all test shots in the data base. Since the Workshop some of this effort has been published in AFWL-TR-81-223, Summary of Trapped Electron Data, by Dr. K. Pfitzer.

Dr. E. Stassinopoulos presented a short summary of NASA studies of satellite data and their relevance to improved understanding of enhanced radiation belts due to nuclear explosions. He indicated that at L=1.5 the decay of the Starfish-produced belt during the six years following the burst is in very good agreement with the Teague-Stassinopoulos model. Data were derived from OGO-1, OGO-3, OGO-5, and OV3-3.

Dr. C. Crain distributed and presented a summary of a paper by the late Dr. P. Tamarkin on "Trapped Flux Due to Neutron-Decay Betas and Protons from High-Altitude Nuclear Detonations." Trapped electrons and protons are produced on all L-shells due to neutron decay. In the narrow energy range of 12 to 14 MeV Tamarkin's results indicated an order of magnitude greater trapped proton flux at L=2.5 due to nuclear tests in 1958 and 1962 than attributed to the background flux. At other energies the background flux dominated. More relevant to understanding trapped electron radiation and code developments based on the 1958-1962 data were the trapped electron populations from neutron decay calculated to L=6. Although the densities are very low compared with those possible from fission decay betas, they are not low compared with the weak electron population observed at the higher L values in 1958-1962 and attributed to fission decay betas from unexplained debris from the various tests at the higher L shells. Perhaps inclusion of neutrons in computational models can help resolve very important remaining modeling uncertainties. This question is important in assessing the accuracy of high (L=2 to L=6) L-shell trapped densities from mid-latitude bursts at, say, a few hundred kilometers.

C. INJECTION

Dr. John Cladis was the principal discussant in this session. His emphasis was on theoretical aspects of injection of trapped radiation from high altitude fission debris. Numerical results calculated for Starfish and two assumed high altitude detonations were presented. Many of the complex factors involved in injection studies have been analyzed and documented by Cladis and others. Some of the work is presented in the Trapped Radiation Handbook, Chapter 7. Other documentation is presented in DNA and AFWL reports. The accuracy in predicting the

injection of trapped radiation from fission debris is normally highly dependent on the accuracy of debris spatial distribution as a function of time after burst. At burst altitudes where trapping is most efficient, i.e., above a few hundred kilometers, debris location as a function of time after burst needs to be better understood.

In response to a question concerning the levels of trapped radiation which current models estimate will result from various high altitude detonations, two examples were presented.

D. LOSS MECHANISMS AND LIFETIMES

Dr. Michael Schulz gave a comprehensive review of theoretical and observational work he and others have performed in recent years, much of which has been concerned with the natural belts. Due to the great differences in energy spectra for natural and artificial trapped radiation and their L-shell dependence, the work on natural belts is only partially relevant. Schulz's discussion also treated trapped fission electrons. He mentioned that lifetimes of 0.5 MeV electrons are known to range from the order of one week at $L > 3$ to the order of one year at $L \approx 1.5$; lifetimes of 1 MeV electron are about twice as long at each L value. Schulz also reviewed the theoretical progress that has been made in accounting for the dependence of electron lifetimes on energy and L value. He showed a vugraph that depicted the results of work on the levels of stable trapping attainable. This question has been of prime interest since the ARGUS project in 1958. The stable-trapping limit was shown to vary as $(1/L)^4$ as contrasted to the often $(1/L)^6$ dependence based on earth's magnetic field energy. At synchronous orbit altitudes the Kennel-Petshek "stable limit" was indicated as about 3 percent of the "Beta=1" limit.

E. SPECTER DESCRIPTION AND ASSESSMENT

Captain Bob Greaves described in detail the SPECTER (Satellite Protection Environment Codes with Trapped Electron Radiation) Codes, a multistage set of computer codes designed to predict the total radiation flux for any satellite orbit and prescribed high altitude nuclear detonation(s). The mechanical aspects of the codes are fully developed and operational; as better understanding of the many ingredients of the

code (such as injection, lifetimes, as discussed in the workshop) are developed from theory or experiment the code can be improved. This has been the pattern for the past 10 years. The assessment discussion brought out several points of particular interest to the Workshop. These included (1) debris motion is thought to be the greatest cause of uncertainty in calculated environments, (2) the code uses the Kennel-Petchek work described by Schulz (see paragraph above) to establish the "stable-trapping limit," (3) the flux set by the stable-trapping limit is energy dependent, (4) multiple bursts are handled as a linear sum of single bursts, and (5) empirical parameters based on test data interpretation are important contributions to uncertainty in the accuracy of calculated environments.

F. TRAPPED RADIATION--MISSION CONSIDERATIONS

Dr. Gary Cable presented material illustrating how SPECTER and other computational tools can be applied to mission considerations. Vugraphs showing integral electron flux prompt radiation, total dose, and other phenomena were presented for a variety of satellite orbits and nuclear scenarios.

Dr. Ed Divita described JPL work which, among other things, compared Earth and Jupiter trapped electrons and various approaches to spacecraft radiation hardening which have been used in the different environments encountered in space exploration. Typically several man years' work is involved in hardening design. Results have been good as there have been no major radiation damage effects--only an occasional problem with reset, or similar phenomena.

Dr. Joel Fedder briefly reviewed the results to date of work at the Naval Research Laboratory on the effects of magnetospheric detonations (such as a 1 MT burst at several earth radii). This work is motivated by thoughts that very large (several earth radii) magnetic cavities may be possible, hence current trapping considerations would require vast modifications.

G. ASPECTS OF HARDWARE VULNERABILITY

Dr. Verne Josephson provided a comprehensive review of current and projected hardware hardening technology and applications. He also gave a review of the HURON KING underground nuclear test results for the DSCS III program. Of particular interest was a chart showing estimated satellite hardening costs as a function of hardness level to be achieved. Dr. Josephson also shared his thoughts on other satellite hardening problems. He was concerned with (1) ill defined and unsubstantiated threat effects, (2) program funding schedule, weight, and technology, (3) inadequate user requirement definition, and (4) neophyte support/criticisms.

Mr. William Price presented a review of work on "Total-Dose Radiation Effects" at JPL. NASA programs requiring radiation hardening were listed as Voyager I and II, Galileo Orbiter, Galileo Science, and Galileo Probe. The Galileo work is virtually complete and the considerable JPL hardening work and flight experience may be applied to military projects.

H. SINGLE EVENT PHENOMENA

Although the Workshop's primary focus was on the effects of enhanced radiation belts from high altitude nuclear explosions, other phenomena which may cause difficulties in space systems were discussed. In addition to vulnerability of circuit components to total dose and dose-rate radiations, dielectric charging due to large fluxes of energetic electrons and so-called single-particle effects due to transversal of cosmic-ray nuclei though solid-state devices have become of concern. Dr. James Ritter discussed experiences of satellites undergoing single event phenomena and outlined proposed future work, including a satellite experiment, CRRES, directed toward observing both upset effects and the nature of the space environment simultaneously. Goals of CRRES relevant to enhanced radiation belt interests would include space tests of microelectronic devices, directly related energetic particle spectra, and radiation dosage-to-circuit performance in space, and would aid in the understanding of the dynamics of the belts to develop trapped-particle prediction codes.

Dr. Ed Peterson discussed the technical understanding of single event phenomena including characteristics of the environment, device upset cross sections, orbital sensitivity, and susceptibility of such hardware as NMOS, CMOS-Bulk, CMOS-SOS, and I^2L.

Mr. William Price discussed his work at the Jet Propulsion Laboratory on single-particle upset of semiconductor devices. He presented a spacecraft history of single event upsets which show that upsets have occurred in electronic devices on several U.S. spacecraft. Both soft errors (bit flips, change of state, etc.) and latch-up effects have been induced in semiconductor devices in laboratory tests with heavy ions. Upset threshold data were presented for a number of device types and impinging ions including protons and neutrons. His conclusions were that modern devices will upset, that at present bipolar devices are most sensitive, and that as devices get smaller the upset sensitivity will increase.

I. OTHER CONTRIBUTIONS

Dr. Richard McEntire discussed planning at the Applied Physics Laboratory and the Max Planck Institute for a chemical release satellite (lithium and cesium) to operate in the 1984-1985 time period. Two releases would be made in the solar wind in front of the magnetosphere, and artificial comet release in the magnetosheath, and four releases would be made inside the magnetosphere in the magnetotail region. This experiment was thought to have several features which can aid our understanding of trapped radiation--in particular, lifetime at high L values and the validity of the Kennel-Petchek "stable limit."

Dr. E. Stassinopoulos discussed the radiation effectiveness for electrons, protons, and gammas on integrated circuit board soft devices. Comprehensive tests have confirmed that, in terms of observable effects per unit dose, the different radiation sources and energies are not equivalent. Annealing measurements have also revealed the existance of two activation energies and a significant differentiation in the recovery characteristics of parts exposed to electrons or protons only. One feature of these tests, relating to dose-rate effects, has been that, in general, the hardware on satellites outlived its predicted

lifetime. Workshop members gave their thoughts on annealing phenomena, short vs. long time radiation doses and the possible impact on reasonably predicting hardware lifetime in nuclear vs. natural environments.

III. SUMMARY COMMENTS

In summary, the Workshop discussed many topics most relevant to enhanced radiation belts and their potential effects on the architecture of enduring space systems. As the various discussions indicated, much progress has been made over the past two decades; however, important deficiencies remain. Topics amenable to significant improvement and for which new or continuing work is recommended included:

- perspective on enhanced radiation belts and enduring space systems
- debris motion--theory, experiment, chemical releases
- injection--theory and operational considerations
- stable-trapping limits--theory and experiments
- lifetimes
- test data interpretation
- neutron decay injection and effects on test data interpretation
- phenomenology of very high altitude detonations
- nonlinear effects
- multiple burst effects--heave, magnetic disturbances, etc.
- natural environment--new experiments on factors relevant to nuclear effects, proton belt enhancement, single event phenomena, etc.
- hardware issues--annealing, dose effectiveness, dose rate effects, etc.

Time did not permit formulating specific research suggestions in each of the above areas; however, to some extent suggestions for theoretical and experimental opportunities appear in the discussion of session activities in this Note. An item not discussed in the Workshop but which should be added to the above list is the role of trapped radiation induced noise in sensor focal planes. This topic has recently surfaced in system trade-off studies and appears important.

The comprehensive review of the national effort devoted to needed understanding of enhanced radiation belts indicated that the current effort is minimal. It is clear that improvements needed to resolve major phenomena and operational employment questions and their role in influencing the preferred architecture for survivable and enduring strategic systems will require much greater support than exists at present.

APPENDIX I

ADDRESS LIST
WORKSHOP ON ENHANCED RADIATION BELTS
AND SYSTEM IMPLICATIONS
27 and 28 JULY 1982
The Rand Corporation
Santa Monica, California

1.	Dr. J. Bernard Blake Aerospace Corporation Mail Station M-2 259 P.O. Box 92957 Los Angeles, CA 90009	(213) 648-7078
2.	Dr. Gary Cable Computer Sciences Corporation 1400 San Mateo Blvd., S.E. Albuquerque, NM 87108	(505) 265-9571
3.	Dr. John B. Cladis Lockheed Palo Alto Research Laboratory 3251 Hanover Street Palo Alto, CA 94304	(415) 858-4122
4.	Mr. Ed Divita Jet Propulsion Laboratory Mail 144-218 4800 Oak Grove Drive Pasadena, CA 91109	(213) 354-3041
5.	Mr. Joel Fedder Code 4780 Naval Research Laboratory Washington, D.C. 20375	(202) 767-3630 or 767-6780
6.	AFWL/NTYCE Attention: Captain Robert Greaves Kirtland Air Force Base New Mexico 87117	(505) 844-0106
7.	Dr. Al Grossman L-10 Lawrence Livermore National Laboratory P.O. Box 808 Livermore, CA 94550	(415) 422-6513

8. AFWL/NTYCE (505) 844-0106
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APPENDIX II

AGENDA

WORKSHOP ON ENHANCED RADIATION BELTS AND SYSTEM IMPLICATIONS
27 and 28 July 1982

Tuesday, 27 July 1982

8:30 a.m.	Registration	30*
	Opening Comments Dr. Sherman Karp, DARPA	10
	Review of Past and Current Programs Dr. Joseph Janni, AFWL	40
	Review of Artificial Belts Dr. Martin Walt, Lockheed	80
	Injection Dr. John Cladis, Lockheed	120
	Loss Mechanisms and Lifetimes Dr. Michael Schulz, Aerospace	120

Wednesday, 28 July 1982

8:30 a.m.	SPECTER Description and Assessment Captain Bob Greaves, AFWL	90
	Trapped Radiation--Mission Considerations, Dr. Gary Cable, CSC	30
	Aspects of Hardware Vulnerability Dr. Verne Josephson, Aerospace	120
	Single Event Phenomena Dr. James Ritter, NRL	40
	Other Contributions	30
	Synthesis - Workshop Participants	90

The names listed above will coordinate, introduce and chair the workshop session. Those having contributions for any session should make the chairman aware of their inputs and time requirements.
*The budgeted time in minutes for each item.